ACCURACY OF DIGITIZATION USING AUTOMATED AND MANUAL METHODS

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INTRODUCTION: The proliferation of three-dimensional (3-D) motion measurement systems has lead to numerous studies addressing the accuracy and precision of these systems (Klein and DeHaven, 1995; Scholz, 1989; Scholz and Millford, 1993). The limits of the systems' accuracy have been the most frequently reported measure on which to base decisions regarding the suitability of a specific system. The accuracy and precision are usually provided by the manufacturer to allow users to evaluate the efficacy of such systems within the context-dependent needs of their laboratories.

A systems' accuracy is measured as the degree of agreement between a reference standard and the reconstructed estimates of that standard. There has been general agreement in the literature that each user should determine the limits of their system's accuracy in order to provide a basis for making inferences based on the data.

The purpose of this study was to evaluate the error created in kinematic estimates using manual digitization. To create as realistic a scenario for sports biomechanics research as possible, multiple digitizers were used. Each digitizer performed a manual reduction of the same images to allow for inter-digitizer comparisons. The hypothesis for the investigation was that manual digitization results in clinically acceptable angular estimates under dynamic conditions.

METHODS AND PROCEDURES: Two Panasonic AG-455P video camcorders were placed at 30° angles relative to the activity plane for filming. Film speed was 60 Hz, with a shutter speed of 1/500 second. A single 300-W flood light was positioned beside each camera to illuminate the retroreflective markers.

The testing equipment consisted of a rigid T-shaped pendulum suspended by the bottom edge. The pendulum was fastened to a piece of plywood, which served as the background, by a metal bolt. The bolt served as the axis of rotation, and non-planer movement about the bolt was minimized. Eight, spherical, 1.90 cm diameter styrofoam balls wrapped in retroreflective tape were secured to the pendulum with double-sided tape. The background plywood and pendulum were painted black in order to minimize reflections.

The pendulum's trajectory was videotaped using four angular velocities - including static. The angular velocities were produced by rotating the pendulum about its axis (from vertical), to either 45°, 90°, or 120° for release. The angular position of the pendulum was verified prior to each trial using an angle locator (Johnson level & tool Mfg. Co. Inc., Mequon, WI). Ten trials at each of the four angular velocities were videotaped.

The eighty independent film clips (4 angular velocities X 10 trials X 2 views) were manually digitized across 20 frames by five experienced digitizers. Each digitizer had a minimum of 16 weeks (an academic semester) experience in manual digitization. Data produced by each digitizer had been compared to standards to verify their accuracy in previous projects.

Variability scores (error) for each angle were calculated by subtracting the reconstructed 3-D angle from the calculated reference angle. Dependent variables included the pendulum's release position (POSITION), the angles formed by the markers attached to the pendulum (ANGLE), the 20 frames digitized for each trial (FRAME), and the six (including the auto-digitizing) digitizers (RATER). A four-factor (POSITION X ANGLE X FRAME X RATER) analysis of variance (ANOVA) with repeated measures on each variable was used to evaluate accuracy. ANGLE and FRAME were treated as blocking variables to eliminate any interactions with POSITION or RATER.

Intra-class correlation coefficients (ICCs) were used to estimate the variability within release positions (across frames). ICCs were calculated for each RATER within each release position.

RESULTS AND DISCUSSION: The mean errors for each of the digitizers was within ±1°. Similarly, the mean error of the estimates of each of the twelve angles was within ±1°. The largest error associated with the angles were found to have a mean error of 0.555° and 0.502°. Although these angles were two of the largest estimated, no clear pattern of error associated with angle size was evident.

Each of the main effects, and the POSITION x RATER interaction were statistically significant ($\underline{p}$ < 0.0001) (see Table 1). Therefore, we tested for a RATER effect within each POSITION, and a POSITION effect within each RATER.

Table 1. Summary of ANOVA effects for the overall general linear model.

Source	DF	SS	MS	F	p
Position	3	48.84	16.28	115.42	0.0001
Rater	5	76.47	15.29	108.44	0.0001
Position x-Rater	15	17.06	1.14	8.07	0.0001
Angle	11	4650.97	422.82	2997.95	0.0001
Frame	18	637.51	35.42	251.13	0.0001

RATER (digitizer) effects: The overall ANOVA for each of the four release positions were statistically significant ($\underline{p}$ < 0.0001). Tukey's multiple comparisons test for each release position revealed the mean error of the auto-digitized trials to be statistically larger ($\underline{p}$ < 0.01) than the mean error of most of the manual digitizers. The results of the Dunnett's test confirmed that the mean error of the auto-digitized trials was statistically larger ($\underline{p}$ < 0.0001) than all of the manual digitizers (except RATER 3 for the static trials) for each of the four release positions.

POSITION (angular velocity) effects: A three factor ANOVA was employed to determine whether there was a POSITION effect within each RATER. Multiple comparisons were performed using Tukey's multiple comparisons procedure. For the auto-digitized trials the static trials produced statistically less ($\underline{p}$ < 0.05) mean error than the three dynamic conditions.

Rater consistency

The ICC revealed a high degree of reliability among all the digitizers. The range of

ICCs (0.999 to 0.703) reflects a general consistency in digitization. In all but one case (RATER 4), the highest ICC was for the static trials. However, there was not a consistent trend of decreasing reliability with increasing angular velocity (release position).

At the range of angular velocities used in this investigation, both experienced manual digitizers and auto-digitization produced excellent accuracy (± 1.0°). The error associated with the auto-digitized trials agreed with the error ranges reported by other authors. No consistent error increase was found to be associated in a consistent manner with increasing angle size or increasing angular velocity (release position). However, a trend toward increasing error with increasing angular velocity was revealed, with all but one manual digitizer having their least error while digitizing the static trials.

The auto-digitized trials contained statistically greater error ($\underline{p} < 0.0001$) than the manually digitized trials. The reason for the greater error within the auto-digitized trials was unclear, however, we speculated that lighting conditions may have produced digitizing error specific to auto-digitization. While filming an object in motion, lighting conditions may produce errors in centroid identification. Centroid calculations are based upon the mathematical center of all pixels identified above a threshold light level. In our laboratory we have identified varying pixel configurations as lighting conditions are altered due to the motion of the object being videotaped. In contrast, manual digitizers have the advantage of a spherical presentation of markers, even if the shading conditions of the marker are inconsistent.

CONCLUSION: This investigation reported limits of accuracy for the Ariel Performance Analysis System™ for auto-digitization and manual digitization. Clinically acceptable (±1.0°) accuracy was reported for each digitization method, despite statistically larger error for the auto-digitized trials.

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